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RESEARCH MEMORANDUM

COMPARISON OF MEASURED EFFICIENCIES OF NINE TURBINE DESIGNS WITH EFFICIENCIES PREDICTED BY TWO EMPIRICAL METHODS

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RESEARCH MEMORANDUM

COMPARISON OF MEASURED EFFICIENCIES OF NINE TURBINE DESIGNS WITH EFFICIENCIES PREDICTED BY TWO EMPIRICAL METHODS

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SUMMARY

In the study of turbine-power producing characteristics for various applications, a method for predicting the performance of typical turbines is a valuable tool. Efficiencies predicted by the method of Ainley and the method of Kochendorfer and Nettles are investigated and compared with efficiencies determined by experimental study of nine high-work-output turbine designs.

The actual losses for these turbine designs were higher than those predicted by the two methods. Coefficients supplied by Ainley and a value of blading-loss parameter of 0.4 were used in the methods of Ainley and of Kochendorfer and Nettles, respectively; the differences in efficiency were as much as 0.09 for Ainley's method and 0.07 for the method of Kochendorfer and Nettles. For the method of Kochendorfer and Nettles, the values of blading-loss parameter, which produced agreement between measured and predicted efficiencies, range from 0.63 to 0.87. Because the values of blading-loss parameter have no discernible trend, empirical generalization of these blading-loss parameters was not made.

The method of Kochendorfer and Nettles is sensitive to alteration of the assumption governing the computed value of the supercritical-flow deflection and is sensitive in varying degrees to the computed loss due to overexpansion. For two of these turbine designs, a blading-loss parameter which produced agreement between the predicted and measured efficiencies at the design points produced close agreement over a wide range of total-pressure ratios and for blade speeds as low as two-thirds of design blade speed.

INTRODUCTION

In the study of turbine power-producing characteristics for various applications, a method for predicting the performance of typical turbines is a valuable tool. Empirical methods for predicting turbine performance are presented in references 1 and 2. In reference 1, a comparison

is made between the measured and predicted efficiencies of 11 turbine designs at their design points. Reference 1 furnishes all necessary loss data in the form of curves of loss coefficients plotted as empirical functions of various elements of blading geometry. The method of reference 2, however, requires selection of a value of blading-loss parameter in order to predict turbine efficiency; in this reference the 2218
value of the blading-loss parameter for one particular commercial aircraft gas turbine is determined. An additional advantage of the method of reference 2 is that once a value of blading-loss parameter has been chosen, the method provides information on off-design-point as well as design-point performance.

The comparison presented herein was made at the NACA Lewis laboratory

(1) To determine how closely the method of reference 1 predicts the design-point efficiencies of nine turbine designs whose measured performances were available at the NACA Lewis laboratory.

(2) To determine how closely the method of reference 2 predicts the design-point efficiencies of these nine turbine designs if a blading-loss parameter of 0.4 is employed, the value used to predict satisfactorily the performance of the turbine investigated in reference 2.

(3) To determine the values of blading-loss parameter which must be employed with the method of reference 2 in order to effect agreement between the measured and predicted design-point efficiencies of these nine turbine designs.

(4) To investigate the sensitivity of the method of reference 2 to alteration of the assumptions governing supercritical-flow deflection and overexpansion.

(5) To compare the measured off-design-point performances of two turbine designs with those predicted by the method of reference 2.

The nine turbine blading designs, herein designated A to I, have a single one-dimensional basis and were designed for a single set of service conditions; the design value of over-all total-to-static-pressure ratio is 4.0. For the selected design conditions, the work output per stage for the nine turbine designs is higher than that for the turbine investigated in reference 2 and probably also higher than the work output per stage of the turbines investigated in reference 1. The design techniques employed for the nine turbine designs produce very small radial variations in blade shape and orientation and, as a result, the design values of radial variations in pressure did not balance the radial accelerations. This situation probably adversely affected the rotor-entrance flow direction near the blade ends.

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Throughout this investigation only mean-radius conditions are considered because:

(1) In references 1 and 2, the methods of performance predictions are considered dependent on the geometry only at the mean radius.

(2) The hub-tip radius ratio was comparatively high.

(3) The profile shapes and orientations of both stator and rotor blades varied only slightly with radius.

Actual performances of the nine turbine designs were determined by means of the apparatus and the procedure described in reference 3. Air at 710° R and approximately atmospheric pressure was the driving medium, and the turbine output was based on measured torque. For total-pressure ratios of 2.0 or greater, the probable error in the internal efficiency was about 0.01. The measured over-all performance of the nine turbine designs is presented as well as the design-point performance.

DESCRIPTION OF BLADING DESIGNS

The general design conditions for all nine turbine blading designs are:

Over-all total to static-pressure ratio	4.0
Equivalent mean blade speed, ft/sec	643
Equivalent weight flow per unit frontal area, lb/(sec)(sq ft)	4.69
Hub-tip radius ratio	0.80

One turbine design, which is typical of the nine designs, is described in detail in reference 3. The turbine geometry was determined by dimensional inspection of the actual blade profiles. Pertinent characteristics of the nine turbine designs are presented in table I. The velocity diagrams of the nine turbine designs are such that the stator choked for each design. Because the design conditions resulted in a single stator design, one stator was used for investigation of the entire series of nine turbine designs. Table I therefore primarily relates rotor characteristics. These characteristics, which are tabulated, either are necessary in application of the methods of references 1 and 2 or are employed in investigating variations in the method of reference 2.

RESULTS AND DISCUSSION

The methods of references 1 and 2 are based principally upon velocity-diagram computations. Inasmuch as the over-all total-to-static

pressure ratio, equivalent mean blade speed, equivalent weight flow per unit of frontal area, and hub-tip radius ratio were specified for the entire series of nine turbine designs, only one additional variable remains to be specified in order to determine each velocity diagram completely. Thus, among the nine turbine designs only one additional variable may be specified independent of the others. This variable could be, among others, amount of reaction, stator total-to-static- 2218
pressure ratio, rotor-entrance Mach number, or rotor-exit tangential velocity. For this investigation, amount of reaction was chosen as the basis for classification and as such serves only to identify the various turbine designs and to describe the amount of variation from design to design. Reaction is defined herein as the ratio of static enthalpy drop across the rotor to the isentropic enthalpy drop from inlet total to exit static pressure.

In the performance evaluation of the nine turbine designs, the tangential component of absolute velocity at the rotor exit was assumed to be unrecoverable. Thus, for determination of both predicted and measured efficiency, the exit total pressure was in each case determined by crediting the turbine with only the axial component of velocity.

The over-all performance of each of the nine designs is presented in figure 1. The operating condition for which the total-to-static-pressure ratio is 4.0 and the equivalent mean blade speed is 643 feet per second is designated on each performance map as the design point. Little variation in the general performance characteristics occurs among the nine turbine designs. The design-point efficiency ranges from 0.80 to 0.84 and the maximum efficiency from 0.82 to 0.85 within the range investigated. With the possible exception of design C, the equivalent mean blade speed at the point of greatest efficiency for each design is greater than the design value.

Method of Reference 1

In figure 2, the design-point efficiencies predicted by the method of reference 1 for the nine turbine designs are presented as a function of amount of reaction. For purposes of comparison, the measured values of design-point efficiency are also plotted. The measured efficiencies of all turbine designs are lower than the corresponding predicted efficiencies, the differences varying between 0.03 and 0.09. The increase in rotor-blade lift coefficient of design H, which is associated with increasing blade pitch from 0.278 to 0.396 inch, results in a slightly, but discernably, lower value of predicted efficiency. The measured efficiency is generally considerably lower than the predicted efficiency probably because the work output per stage and the Mach numbers are higher and the radial variation in rotor angle of incidence is more severe for these nine turbine designs than for the turbine on which the correlation of reference 1 is based.

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Method of Reference 2

Values of blading-loss parameter from 0.3 to 0.5 generally encompassed the range of variation in efficiency of the turbine investigated in reference 2. Design-point efficiencies of the nine turbine designs as predicted by the method of reference 2 (assuming a blading-loss parameter of 0.4) are presented in figure 3 with the measured design-point efficiencies. Choice of a blading-loss parameter of 0.4 resulted in an overestimation of the efficiency of the nine turbine designs of 0.03 to 0.07. Choice of a higher value of blading-loss parameter would have resulted in closer agreement between the predicted and measured efficiencies. The spread of 0.04 in the differences would probably have remained about the same if a different, single value of blading-loss parameter had been selected. Choosing appropriate values of this loss parameter for each design requires either a knowledge of the actual turbine performance near the design point or an ability to predict the origin and magnitude of loss.

Because the measured performances of these nine turbine designs are available, the values of measured design-point efficiency were employed to determine the blading-loss parameter for each of the nine turbine designs. The values of blading-loss parameter which result in agreement between the predicted and measured efficiencies are presented in figure 4. In contrast to the values of blading-loss parameter of 0.3 to 0.5 which encompass the range of measured efficiencies in reference 2, figure 4 shows values of blading-loss parameter of 0.63 to 0.87.

The principal differences between the flow conditions in the turbine considered in reference 2 and the nine turbine designs considered herein are (1) the work output per stage is higher, and (2) the radial variations in rotor-entrance angle of incidence are probably greater for the nine turbine designs. Because of a reduced turbine-inlet temperature, the ratio of specific heats used in this investigation was 1.40 compared with 1.34 in reference 2; however, this secondary difference should not increase the calculated turbine losses. The principal differences stated previously are the factors that probably account for the variation in blading-loss parameter between reference 2 and this investigation. No discernable pattern of variation in blading-loss parameter was evident for the nine turbine designs investigated, therefore general conclusions concerning the variation in this parameter were not drawn.

For operation of blade rows at supercritical pressure ratios, reference 2 assumes that for a given change in Mach number the flow-angle deflection at the blade-row exit is that which arises from Prandtl-Meyer expansion of a uniform supersonic stream about a single corner. As discussed in reference 4, the validity of this assumption rests on either prominent wake regions or discontinuity in mass flow.

Overexpansion also influences the performance of blade rows at supercritical pressure ratios. Overexpansion results from excessive channel divergence and produces shock losses generally avoided in turbine design. As shown in table I, designs A, C, and I have channel divergence; these divergences resulted from inaccuracy in manufacture. 2218

In order to investigate the effect of supercritical-flow deflection and overexpansion on performance computations by the method of reference 2, additional values of blading-loss parameter were determined for the following conditions:

(1) One-dimensional continuity was assumed to determine supercritical-flow deflection; this assumption was made for designs A, E, and I.

(2) In addition to the loss computed by use of a blading-loss parameter, an additional loss due to overexpansion was considered for those designs (A, C, and I) having channel divergence. The method of computation remained otherwise unchanged. The values of blading-loss parameter thus determined are presented in figure 5 with the values of blading-loss parameter of designs A, C, E, and I replotted from figure 4.

The values of blading-loss parameter both increased and decreased as a result of changing the assumption governing the computed value of supercritical-flow deflection (fig. 5). This dual variation results from two opposing effects and the direction of the change in blading-loss parameter depends on which effect predominates. One effect occurs at the stator exit and the other at the rotor exit.

As the stator-exit conditions are assumed to vary, the ratio of total pressure (relative to the rotor) to the square root of the total temperature (relative to the rotor) must remain nearly constant if both rotor and stator are to continue to choke; for constant blade speed, this results in only small variations in stator-exit tangential velocity and total pressure and temperature relative to the rotor. The assumed change in supercritical-flow deflection produces a decrease in total-to-static-pressure ratio at the stator exit for the nearly constant stator-exit tangential velocity. In order that the over-all loss shall be constant, the blading-loss parameter must increase because the stator-exit and rotor-entrance velocities are reduced.

As the rotor-exit conditions are assumed to vary, the ratio of total pressure (relative to rotor) to the rotor-exit static pressure is nearly constant; this relation results from the small variations in total pressure relative to the rotor as discussed previously and the constant value of rotor-exit static pressure assigned in design. Changing the supercritical-flow-deflection assumption increased the rotor-exit tangential velocity, thereby increasing both turbine work and leaving loss. Because the increase in leaving loss predominates, the net effect is to decrease the blading-loss parameter.

For design A, the stator-exit total-to-static-pressure ratio is approximately 4.0 and the relative velocity at the rotor exit is slightly subsonic. The effects of change in stator-exit conditions therefore predominate, and the blading-loss parameter increases from 0.70 to 0.89 for design A. For design I, the stator-exit velocity is low relative to the other turbine designs, the relative rotor-exit velocity is supersonic, and the exit tangential velocity is high compared with the other designs. Because the rotor-exit conditions predominate, the result of changing the supercritical-flow-deflection assumption is to decrease the blading-loss parameter from 0.87 to 0.66. The reaction of design E lies between the reactions of designs A and I and thus the blading-loss parameter for design E was reduced by an intermediate amount from 0.68 to 0.60. These results show that the value of blading-loss parameter in reference 2 is sensitive to changes in the assumptions governing supercritical-flow deflection.

The loss due to overexpansion was estimated from the chart in reference 5. Design A, although having channel divergence, was not penalized by a loss due to overexpansion because the computed velocities do not require a supercritical pressure ratio across the rotor. For design C, the channel divergence is very nearly that required for ideal supersonic expansion with the result that a negligible change in blading-loss parameter was obtained. For design I, the blading-loss parameter was changed from 0.87 to 0.82. Thus, the values of blading-loss parameter in reference 2 are sensitive in varying degrees to loss due to overexpansion.

Off-Design-Point Performance by Method of Reference 2

In the course of some earlier work, the over-all performances of designs A and E were computed by the method of reference 2. These predicted performances are compared in figure 6 with the measured performances. For designs A and E, blading-loss parameter of 0.80 and 0.70, respectively, were chosen; therefore exact agreement between the predicted and measured efficiencies was not obtained at the design points; in each case, the predicted design-point efficiency is about 0.01 high. In general, the measured and predicted efficiencies are in close agreement, the maximum difference for blade speeds as low as two-thirds of design blade speed being only 0.05. In particular, at high blade speeds and low total-pressure ratios the agreement is excellent. The lines representing an equivalent mean blade speed of 650 feet per second do not coincide because of the difference between predicted and measured weight flows. Although a discharge coefficient of 0.98 was assumed for both turbine designs, a discharge coefficient of 1.03 produces better agreement. The results for these two turbine designs show that a blading-loss parameter and discharge coefficient which produce agreement between the predicted and measured performances at the design points can be used with good accuracy to predict performance over a wide range of total-pressure ratios and for blade speeds as low as two-thirds of design blade speed. 2218

SUMMARY OF RESULTS

For nine turbine designs incorporating high work output per stage, design-point efficiencies predicted by the method of Ainley and the method of Kochendorfer and Nettles were compared with measured efficiencies. Values of blading-loss parameter which produce agreement between measured and predicted efficiency were determined by the method of Kochendorfer and Nettles. The sensitivity of the method of Kochendorfer and Nettles to alteration of assumptions governing flow conditions was investigated. For two of the nine turbine designs, the off-design-point performance predicted by the method of Kochendorfer and Nettles was compared with the measured performance. The following results were obtained:

(1) Measured losses of the nine turbine designs were higher than the losses predicted by both methods. Coefficients supplied by Ainley and a blading-loss parameter of 0.04 were used in the methods of Ainley and of Kochendorfer and Nettles, respectively; the differences in efficiency were as much as 0.09 for Ainley's method and 0.07 for the method of Kochendorfer and Nettles.

(2) For the method of Kochendorfer and Nettles, the values of blading-loss parameter which produced agreement between measured and predicted efficiencies ranged from 0.63 to 0.87. Because the values of blading-loss parameter had no discernible trend, empirical generalization of these blading-loss parameters was not made.

(3) The method of Kochendorfer and Nettles was sensitive to alteration of the assumption governing supercritical-flow deflection, and it was sensitive in varying degrees to loss due to overexpansion.

(4) For two of the turbine designs investigated, a blading-loss parameter which produced agreement between the predicted and measured efficiencies at the design points produced good agreement over a wide range of total-pressure ratios and for blade speeds as low as two-thirds of design blade speed.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, May 15, 1951.

[redacted]

REFERENCES

1. Ainley, D. G.: An Approximate Method for the Estimation of the Design Point Efficiency of Axial Flow Turbines. Memo No. M. 59, British N.G.T.E., Aug. 1949.

2. Kochendorfer, Fred D., and Nettles, J. Cary: An Analytical Method of Estimating Turbine Performance. NACA Rep. 930, 1949. (Formerly NACA RM E8I16, 1948.)

3. English, Robert E., and Hauser, Cavour H.: Turbine-Rotor-Blade Designs Based on One-Dimensional-Flow Theory. I - Performance of Single-Stage Turbine Having 40-Percent Reaction. NACA RM E9C15, 1949.

4. Hauser, Cavour H., Plohr, Henry W., and Sonder, Gerhard: Study of Flow Conditions and Deflection Angle at Exit of Two-Dimensional Cascade of Turbine Rotor Blades at Critical and Supercritical Pressure Ratios. NACA RM E9K25, 1950.

5. Goudie, William G.: Steam Turbines. Longmans, Green and Co. (London), 2d ed., 1922, pp. 253-255.

TABLE I - CHARACTERISTICS REQUIRED FOR EFFICIENCIES PREDICTED

ACCORDING TO REFERENCES 1 AND 2

[Ratio of specific heats, 1.4; blading-loss parameter, 0.4; discharge coefficient, 0.98; stator throat area, 0.118 sq ft; stator-blade exit angle, 70°; equivalent mean blade speed, 643 ft/sec; blade pitch, 0.278 in.; blade height, 1.47 in. All angles are measured from axial direction.]

	Turbine design								
	A	B	C	D	E	F	G	H	I
Rotor throat area, (sq ft)	0.252	0.224	0.210	0.205	0.202	0.201	0.195	0.194	0.182
Rotor channel diverges	Yes	No	Yes	No	No	No	No	No	Yes
Rotor-blade entrance angle (deg)	44	41	47	41	45	35	42	44	37
Rotor-blade exit angle (deg)	47	52	53	55	55	56	56	58	54
Blade chord, (in.)	0.612	0.635	0.608	0.615	0.641	0.638	0.632	0.622	0.645
Blade pitch, (in.)	0.278	0.278	0.278	0.278	0.278	0.278	0.278	0.396	0.278
Computed ratio of rotor-exit to -entrance axial velocity	0.858	1.162	1.612	1.476	1.616	1.437	1.711	1.679	2.249

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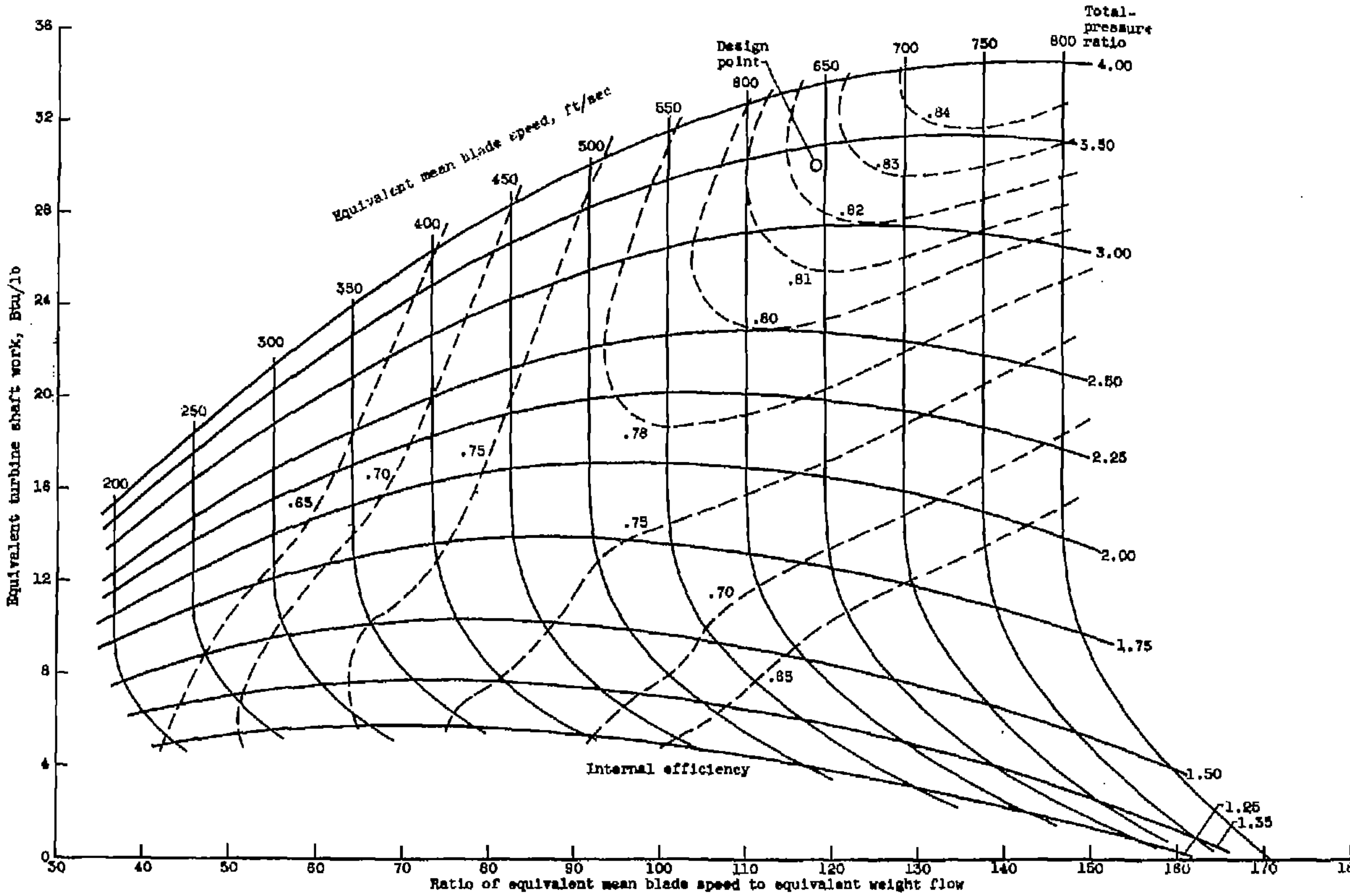
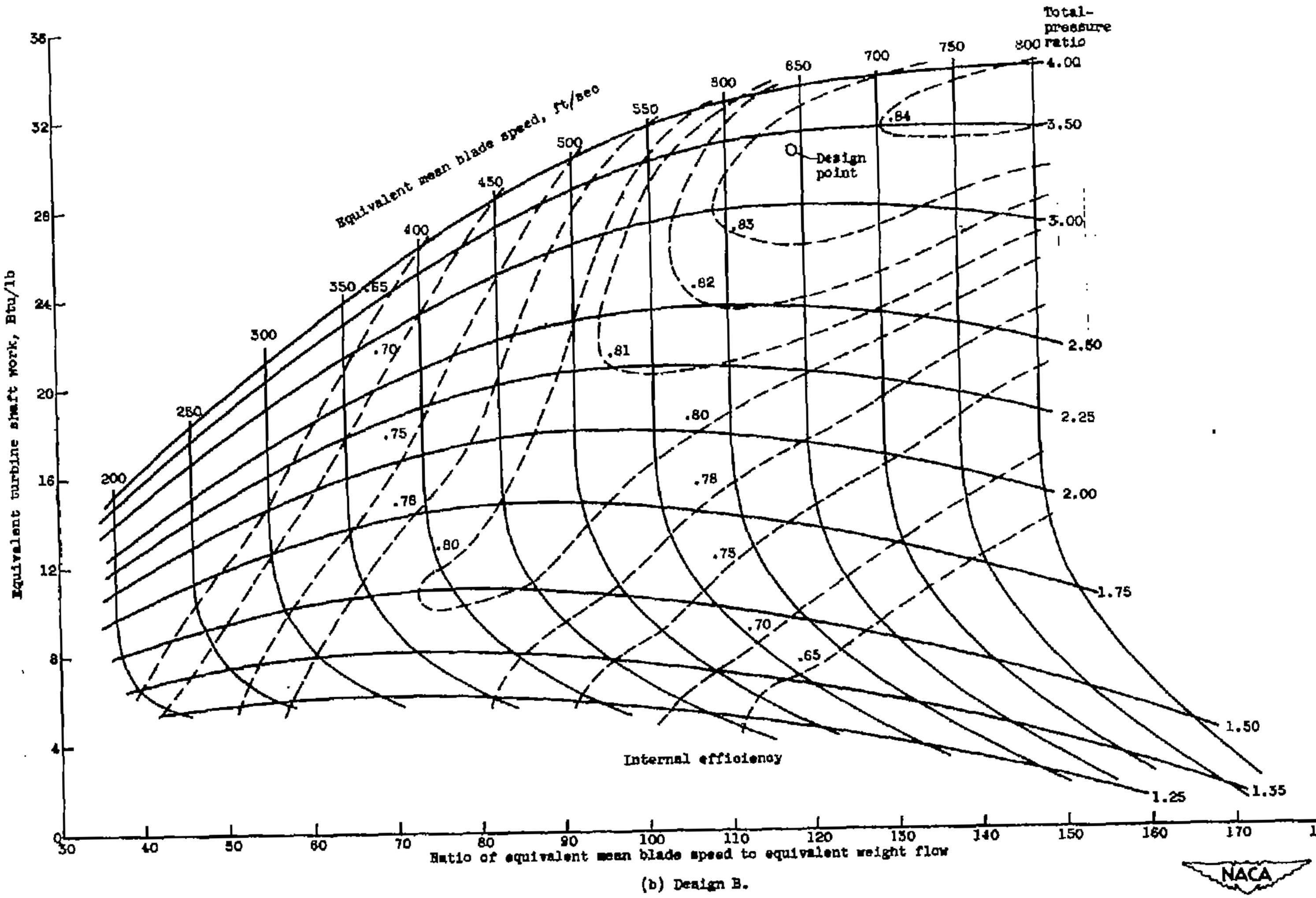


(a) Design A.

Figure 1. - Over-all turbine performance.



(b) Design B.

Figure 1. - Continued. Over-all turbine performance.

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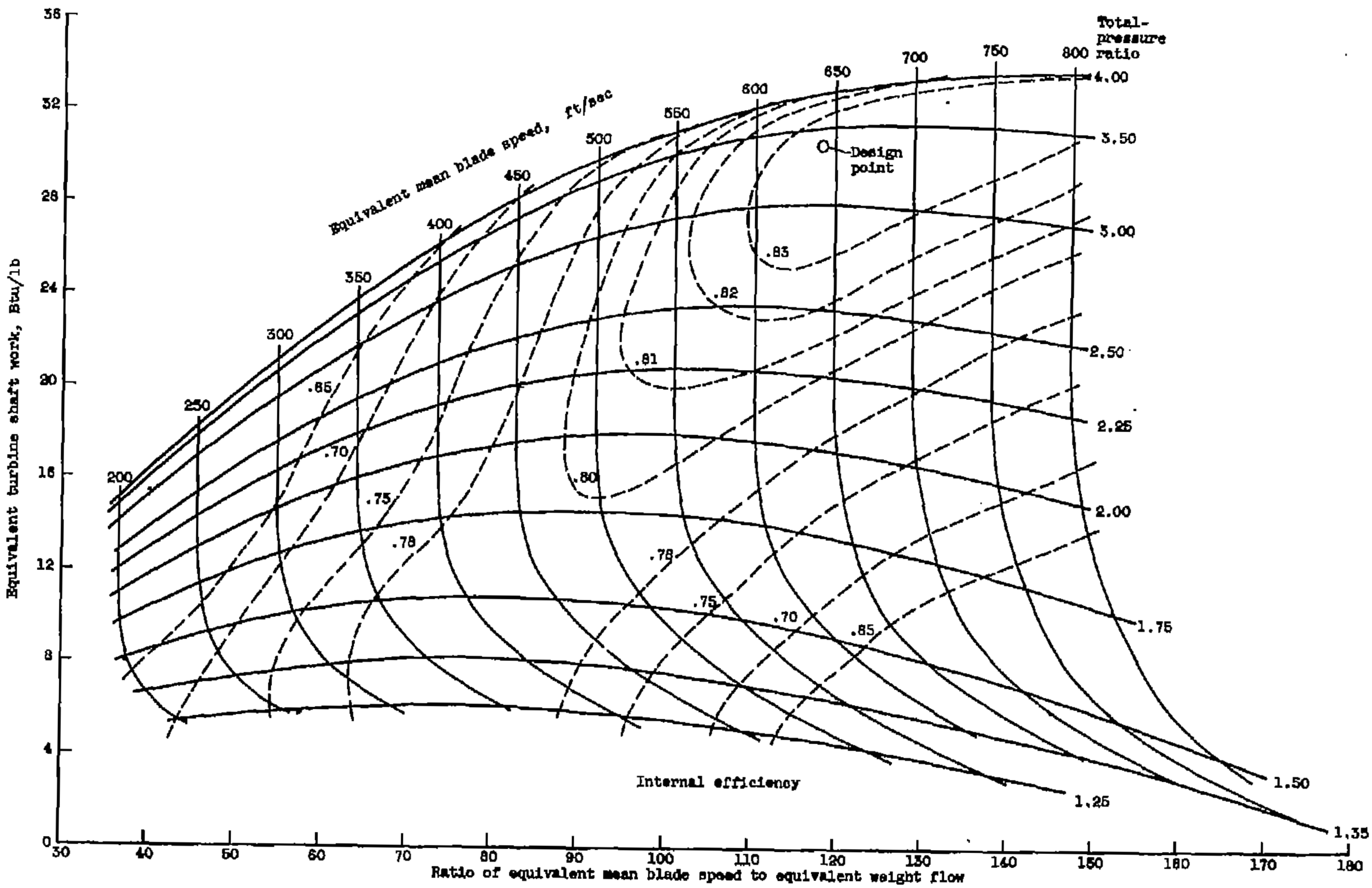

(c) Design C.

Figure 1. - Continued. Over-all turbine performance.

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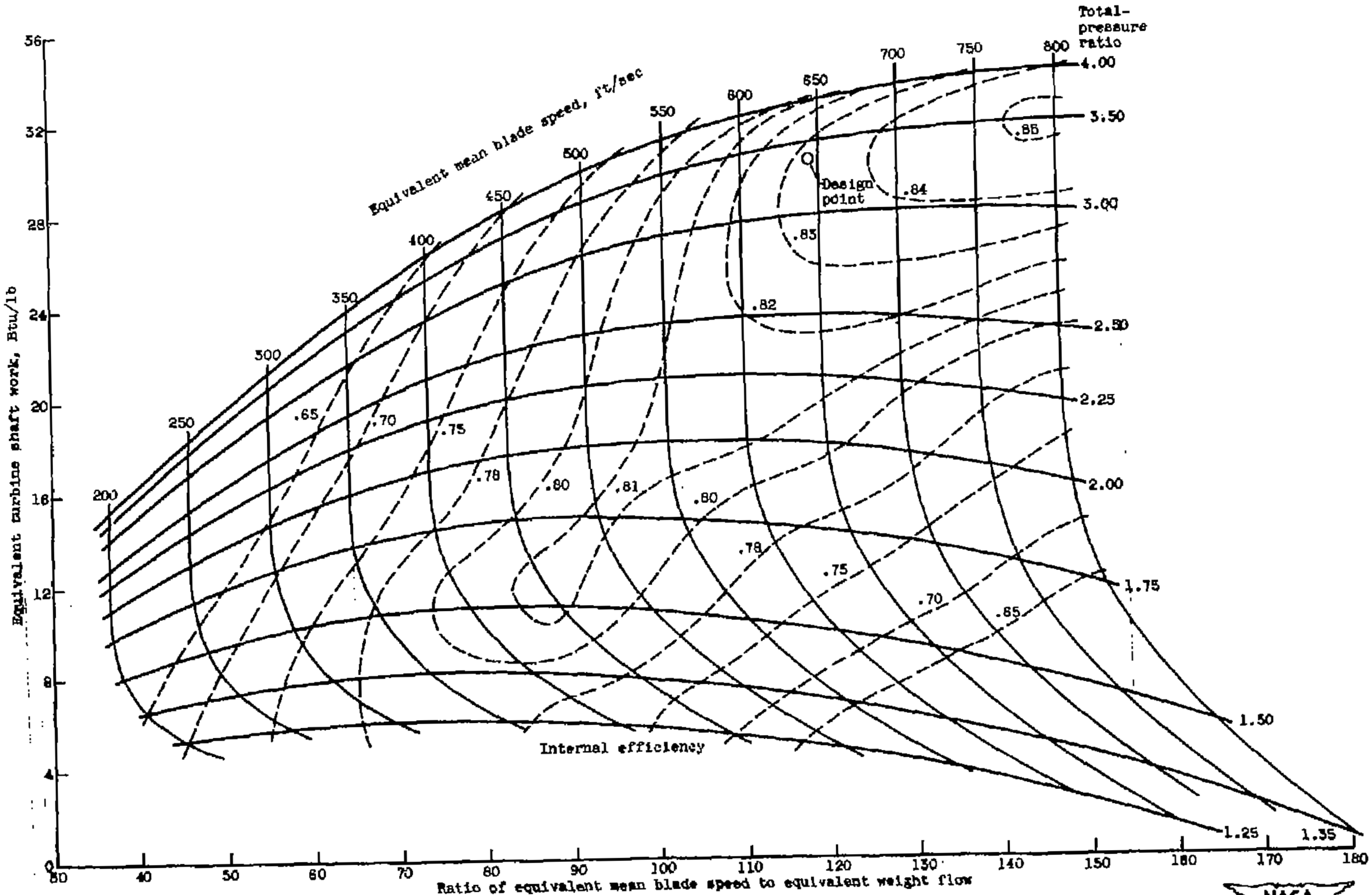

(d) Design D.

Figure 1. - Continued. Over-all turbine performance.

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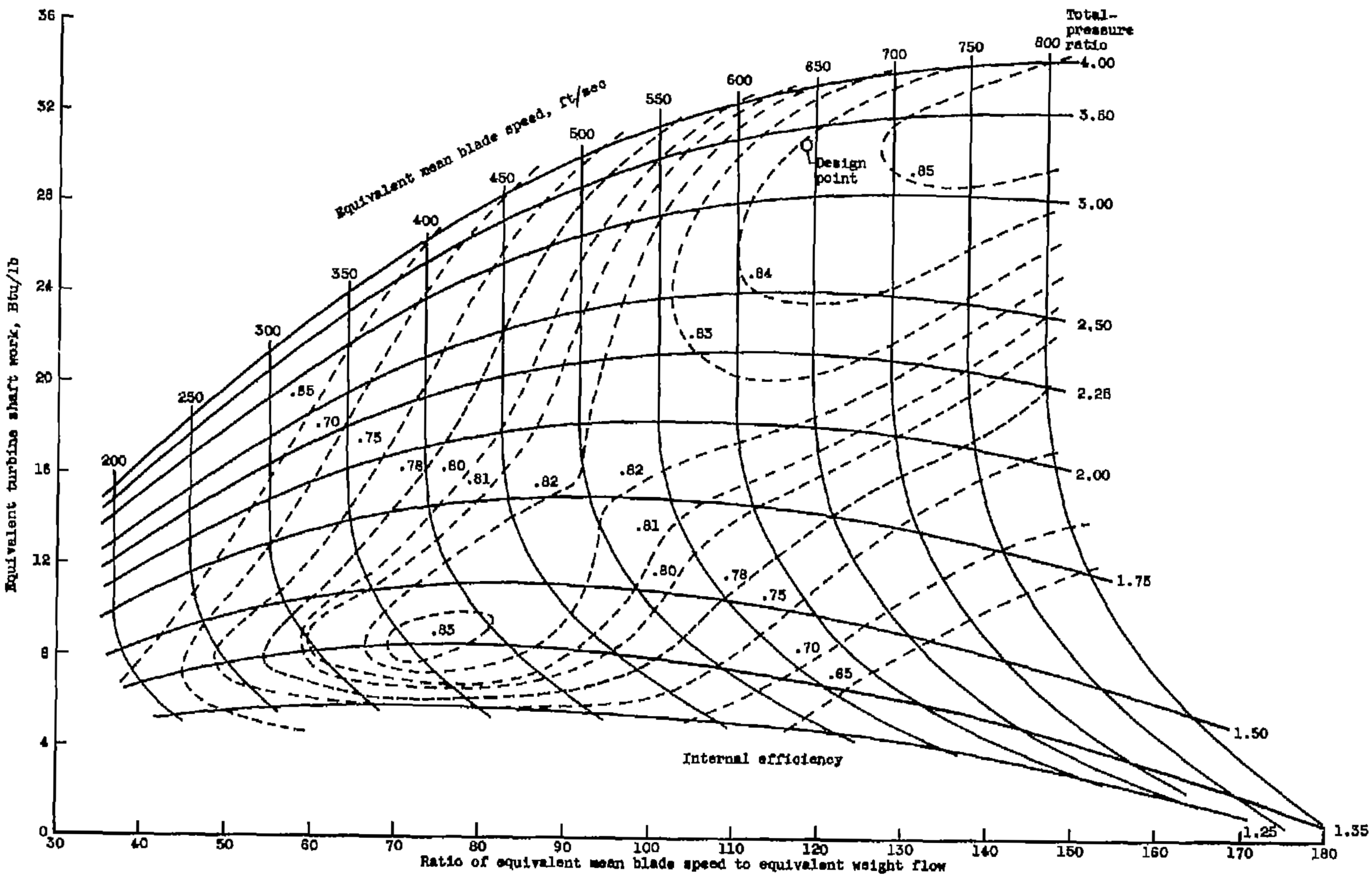

(e) Design E.

Figure 1. - Continued. Over-all turbine performance.

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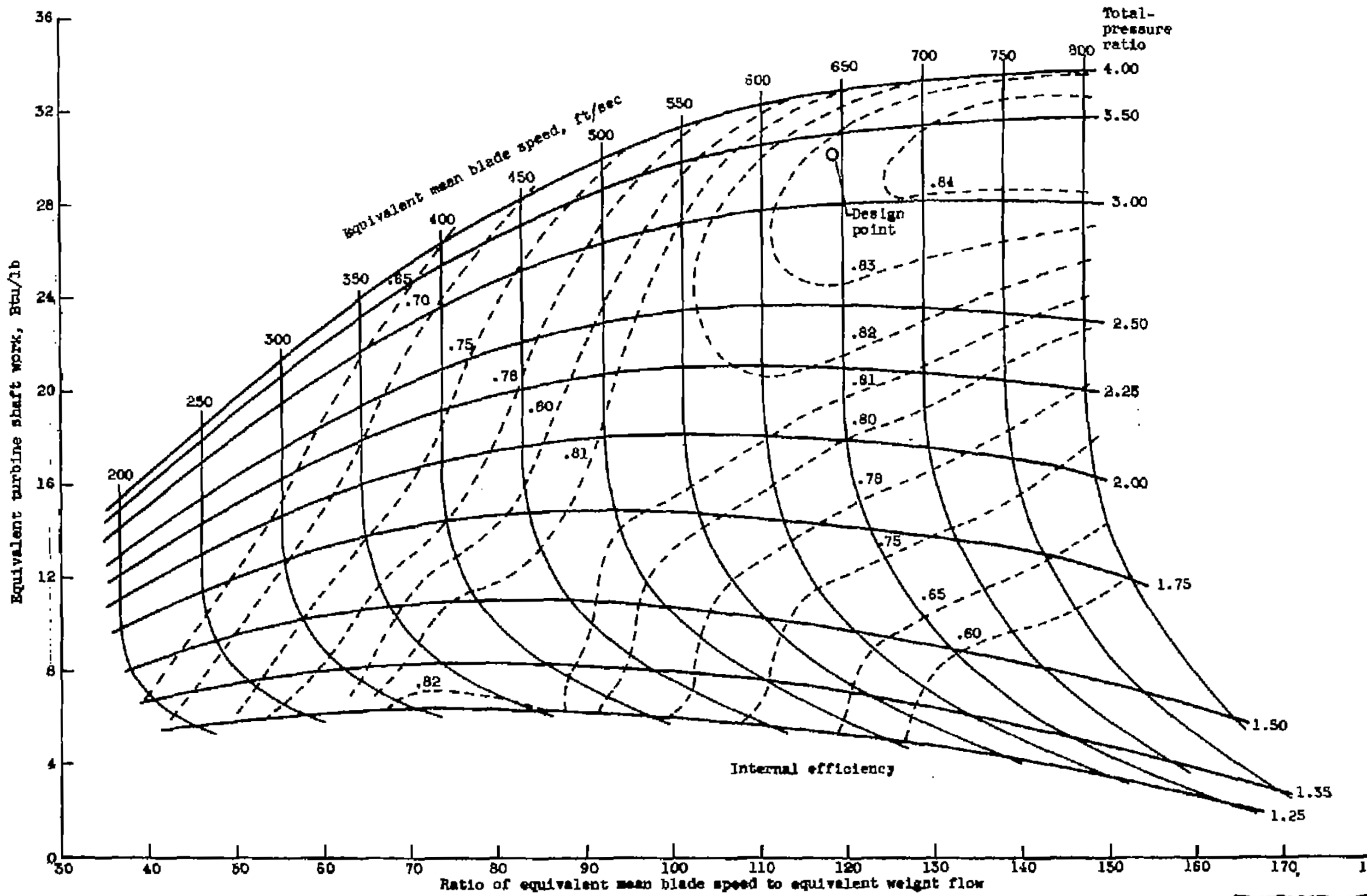
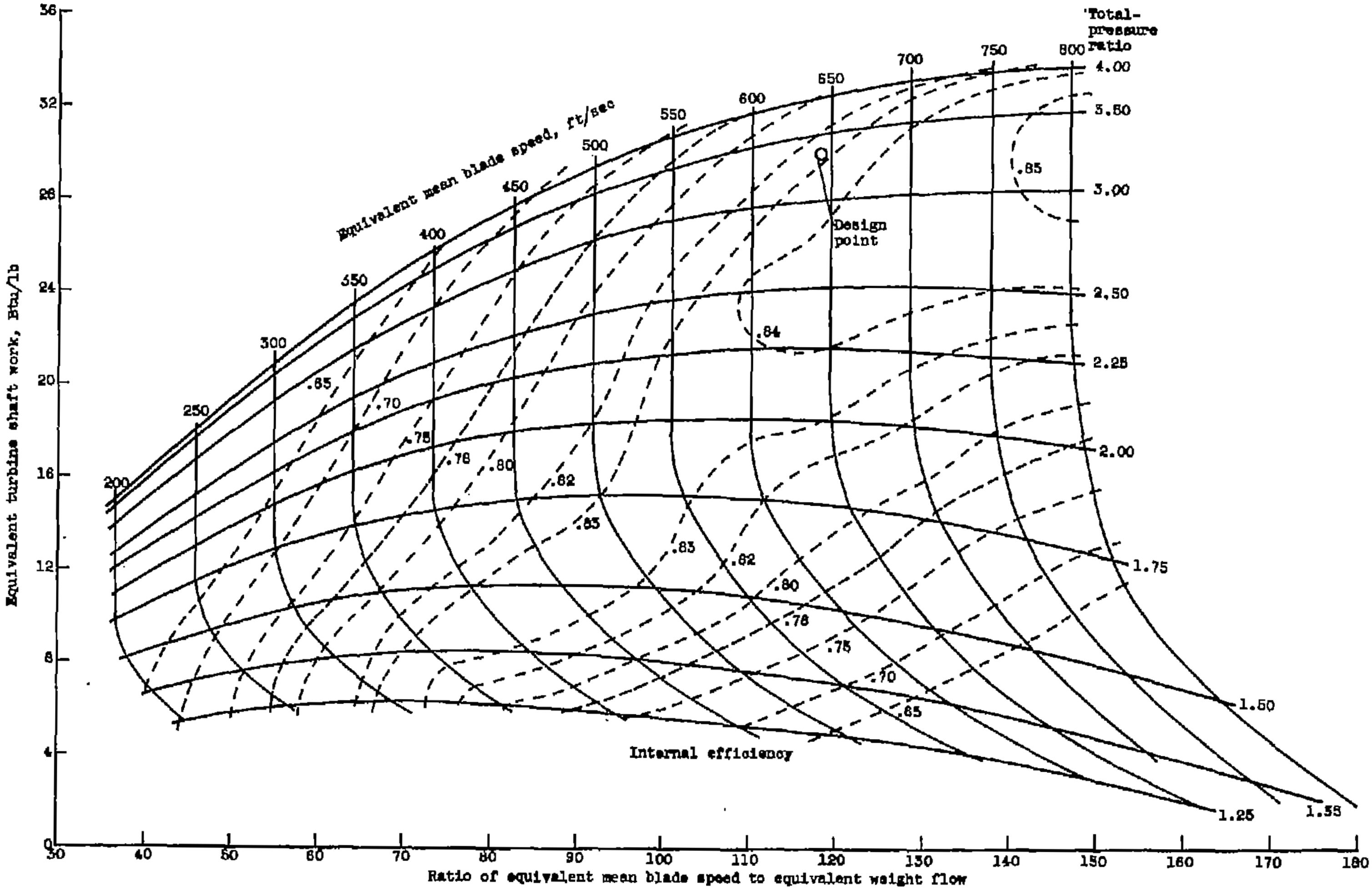


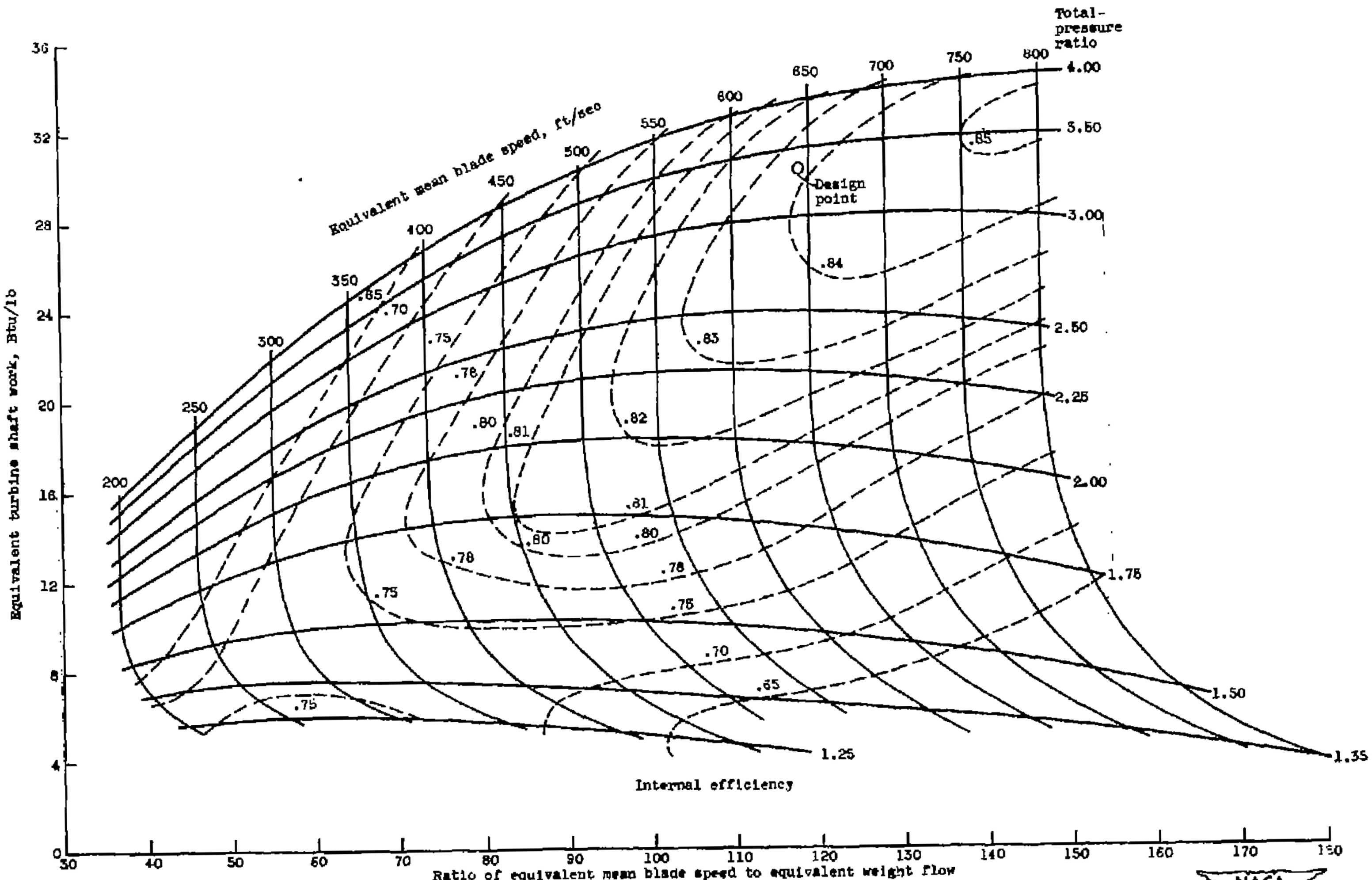
(f) Design F.

Figure 1. - Continued. Over-all turbine performance.



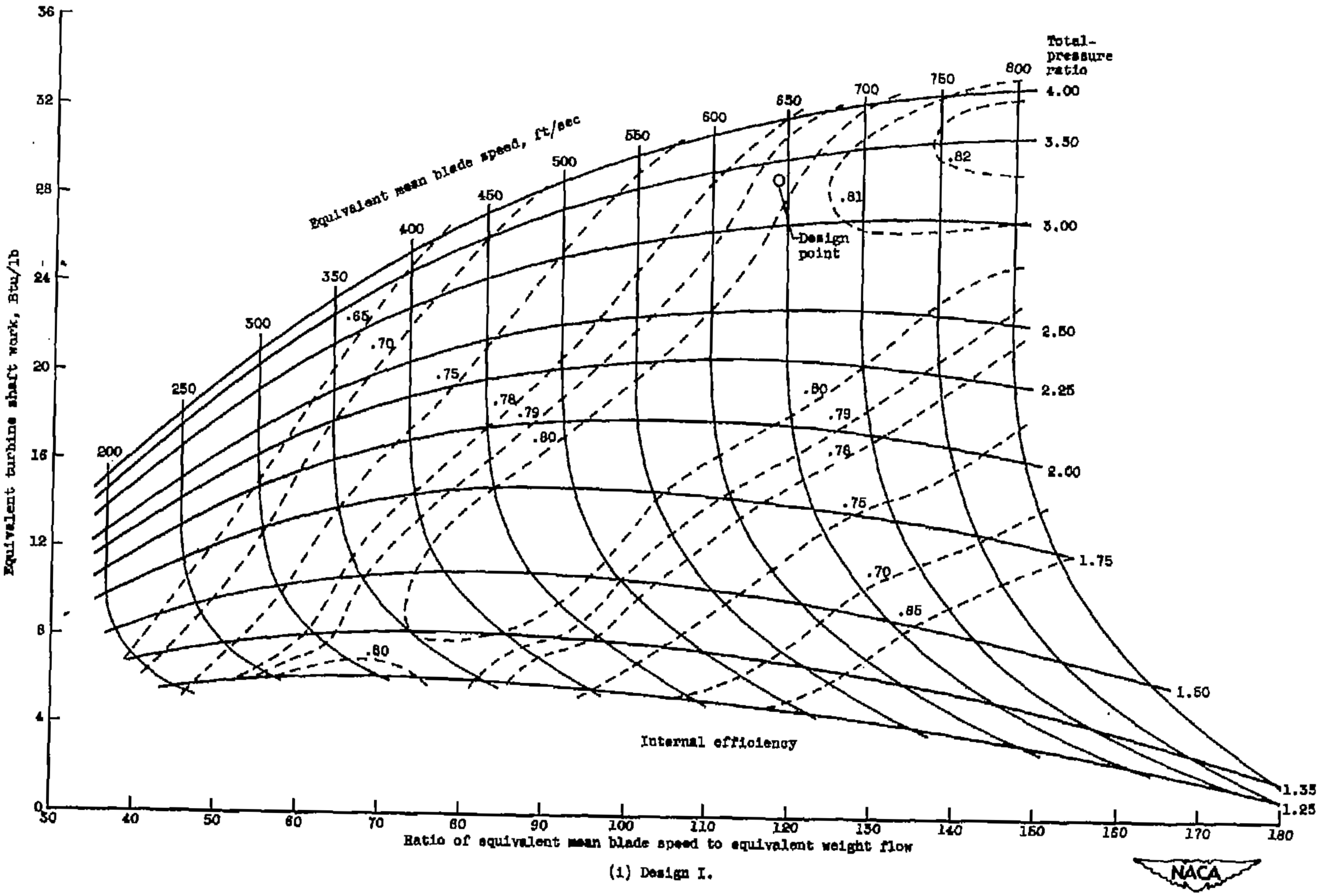
(g) Design G.

Figure 1. - Continued. Over-all turbine performance.



(b) Design H.

Figure 1. - Continued. Over-all turbine performance.



(i) Design I.

Figure 1. - Concluded. Over-all turbine performance.

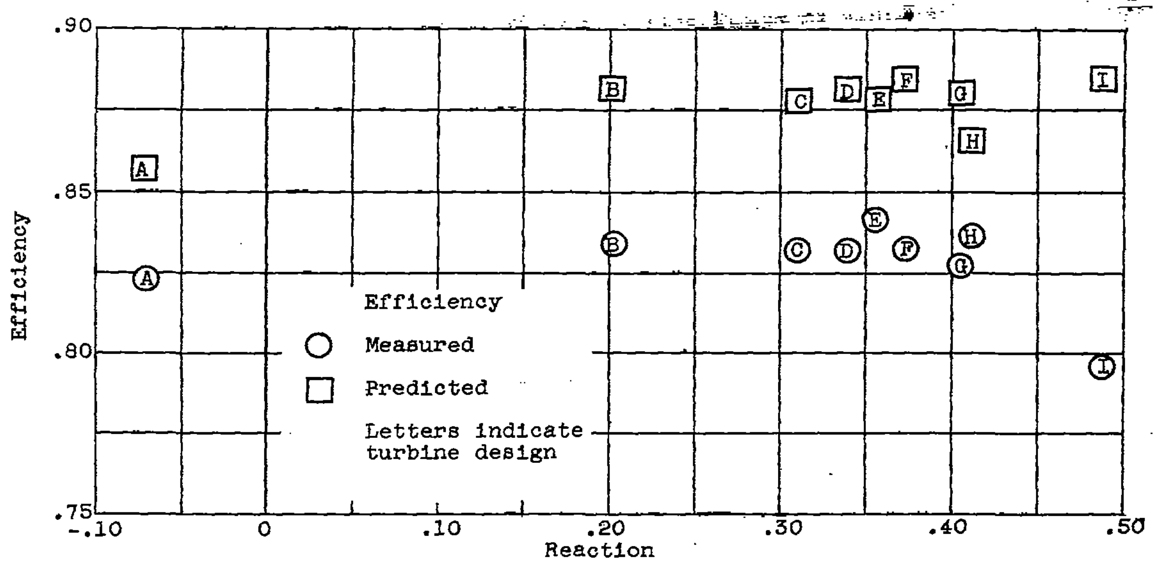


Figure 2. - Comparison of design-point efficiency predicted by method of reference 1 with measured efficiency.

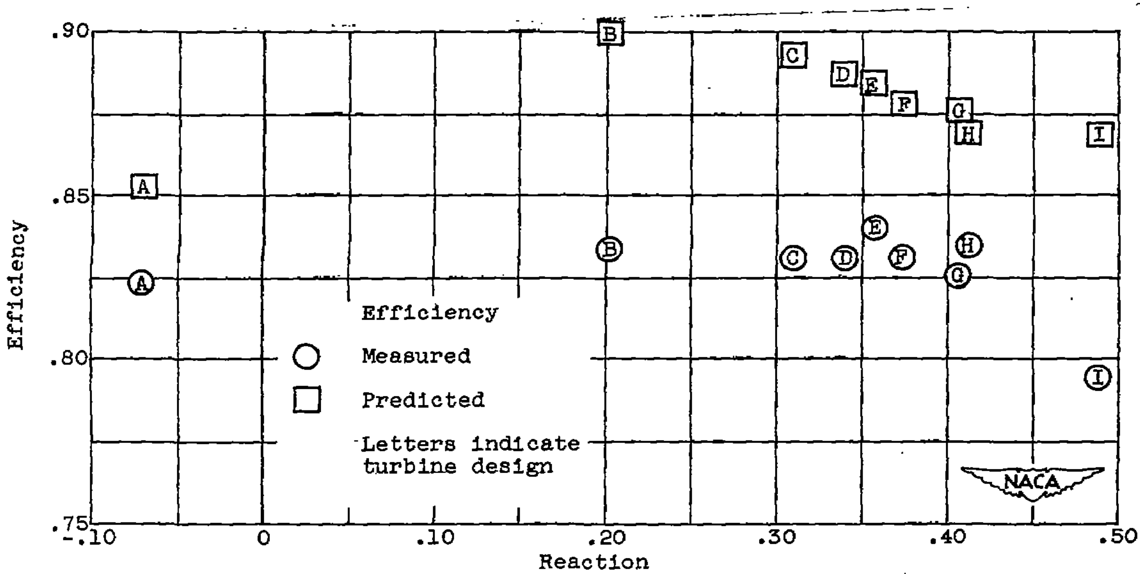


Figure 3. - Comparison of design-point efficiency predicted by method of reference 2 with measured efficiency.

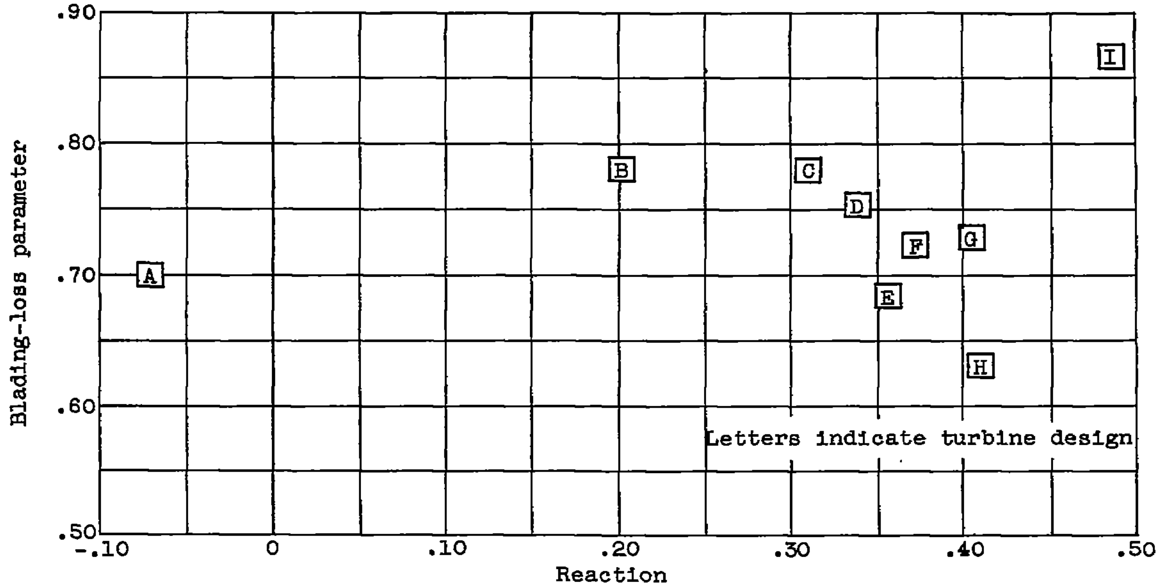


Figure 4. - Blading-loss parameter as determined by method of reference 2. Predicted and measured efficiency coincide at design point.

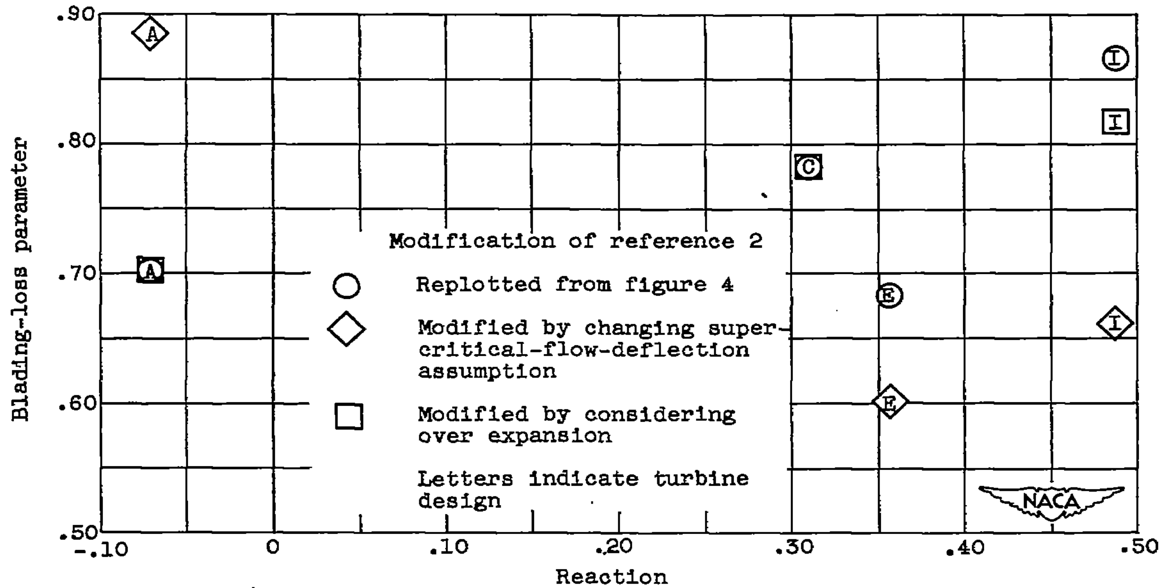
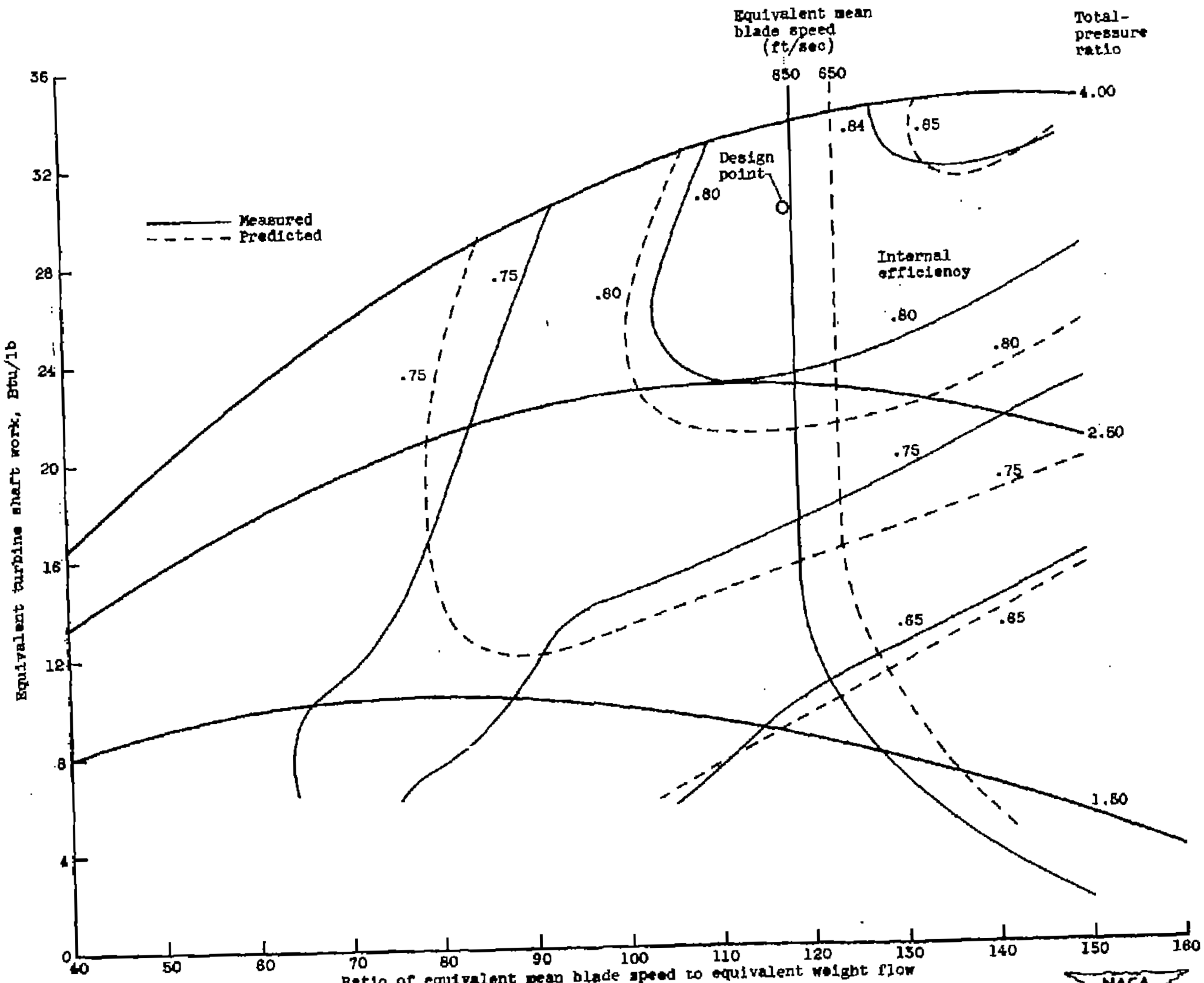


Figure 5. - Blading-loss parameter as determined by modified method of reference 2. Predicted and measured efficiencies coincide at design point.



(a) Design A.

Figure 6. - Comparison of off-design-point performance predicted by method of reference 2 with measured performance.

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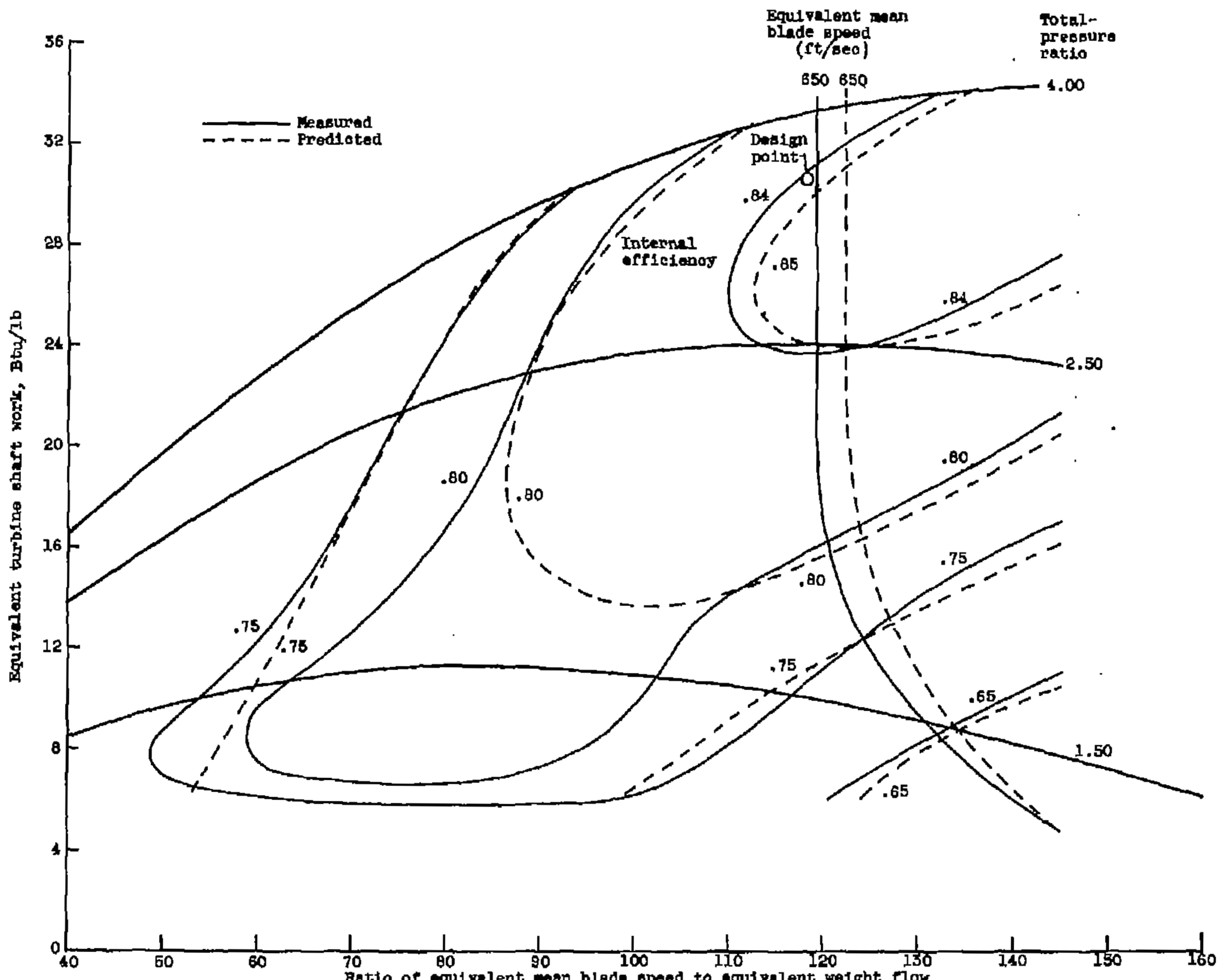

(b) Design E.

Figure 6. - Concluded. Comparison of off-design-point performance predicted by method of reference 2 with measured performance.

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